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The Gamma-Ray Spectrum of the Sun

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Joseph F. Dolan  
Astronomy Department, Harvard University, Cambridge, Massachusetts,  
and N A S A Institute for Space Studies, New York, New York

and

G. G. Fazio  
Smithsonian Astrophysical Observatory  
and Harvard College Observatory, Cambridge, Massachusetts

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Abstract. We investigate mechanisms for the production of gamma radiation ( $h\nu > 10$  kev) by the sun and predict fluxes at the earth. The gamma radiation emitted by the quiet sun is negligible compared to emission during a solar flare. The most important emission mechanism in the 10 kev to 1 Mev energy region is bremsstrahlung by flare-accelerated electrons. The photon spectrum is continuous and decreases monotonically with energy. Flare-accelerated protons will interact with carbon, nitrogen, and oxygen nuclei by inelastic scattering and spallation reactions, producing gamma radiation as a result of nuclear de-excitation. Neutrons resulting from spallation reactions will be partially captured by protons to produce deuterium and 2.23 Mev gamma radiation. The intensity of this line emission is proportional to the neutron density in a flare. Line emission at 0.51 Mev results from positron-electron annihilation. Positrons are produced by beta-decay of radioactive nuclei generated by spallation

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reactions and by the decay of  $\pi^+$  mesons produced in proton-proton reactions. The primary source of photons with energy greater than 50 Mev is the decay of  $\pi^0$  mesons, which are also produced in proton-proton reactions.

Flux estimates indicate that the detection of gamma radiation resulting from a solar flare is feasible and would yield information on nuclear reactions as well as on the intensity and spectrum of high-energy protons and electrons.

*Author*

## I. Introduction

With the advent of high-altitude balloons, rockets, and satellites, it is now possible to investigate all regions of the electromagnetic spectrum of the sun. One region of particular interest is the extreme high-frequency range, where little work has been done before. In this paper we shall investigate the gamma-ray spectrum emitted by the sun and determine what new information about the sun, and solar flares in particular, we can learn from the detection of this radiation. We shall also investigate the various gamma rays to determine which portion of the spectrum is most feasibly detectable and which yields the most direct information on solar-flare structure.

We shall adopt the definition of gamma radiation as any electromagnetic radiation in which the photon energy ( $h\nu$ ) exceeds 10 kev ( $1.60 \times 10^{-8}$  ergs, corresponding to a frequency of  $2.42 \times 10^{18}$  sec<sup>-1</sup> and a wavelength of 1.24 angstroms).

## II. Gamma-ray Production Mechanisms

In general, gamma radiation can be produced by the following mechanisms:

- (1) synchrotron radiation
- (2) electron recombination with atoms (free-bound transitions)
- (3) decay of naturally radioactive nuclei
- (4) inverse Compton effect
- (5) bremsstrahlung (free-free transitions)
- (6) nucleon-nucleon reactions
  - (a) thermonuclear reactions
  - (b) de-excitation of nuclei produced by nuclear bombardment
  - (c)  $\pi^0$ -meson decay
- (7) electron-positron annihilation
  - (a) beta-decay
  - (b)  $\pi^+$ -meson decay

We shall investigate each of the above sources to evaluate the relative intensities and types of spectra produced. To do this, however, we must understand gamma-ray absorption processes on the sun and the physical conditions existing in the quiet sun and in solar flares.

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### III. Gamma-ray Absorption Mechanisms

Although gamma rays may be absorbed or scattered in many ways by electrons, nucleons, electric fields, and meson fields [Evans, 1955], there are three predominant types of interactions: (1) the photoelectric effect, (2) the Compton effect, and (3) electron-positron pair production. The total absorption cross section (including elastic scattering) for a photon of frequency  $\nu$  is given by

$$\sigma_{\nu} = \sigma_{ph} + \sigma_c + \sigma_{pr} \quad \text{cm}^2 \quad (1)$$

where  $\sigma_{ph}$  is the cross section for the photoelectric effect,  $\sigma_c$  for the Compton effect, and  $\sigma_{pr}$  for pair production. The absorption coefficient,  $k_{\nu}$ , is defined by

$$k_{\nu} = \sigma_{\nu} N_a \text{ cm}^{-1} \quad , \quad (2)$$

where  $N_a$  is the number of agents per  $\text{cm}^3$  with which an interaction can occur. The gamma-ray equivalent to the optical depth of visual radiation is given by

$$t_{\nu} = \int_x^{x_0} k_{\nu} dx \quad , \quad (3)$$

where  $x$  and  $x_0$  are the distances from the center of the sun to the source and to the observer. Thus photons of initial intensity  $I_0$ , after traversing a distance  $x_0 - x$  of absorber, will have an intensity  $I$ , given by

$$I = I_0 e^{-t_{\nu}} \quad . \quad (4)$$

Photoelectric Effect. To calculate the photoelectric absorption coefficient over the photon energy range of 10 kev to 10 Mev we must use several different formulas. The main features of the absorption, however, are given [Kaplan, 1956] by:

$$\sigma_{ph} = \phi_0 Z^5 \left( \frac{1}{137} \right)^4 \frac{1}{2} \left( \frac{M_0 c^2}{h\nu} \right)^{\frac{1}{2}}, \quad \text{cm}^2/\text{atom} \quad (5)$$

where

$$\phi_0 = \frac{8\pi}{3} \left( \frac{e^2}{M_0 c^2} \right)^2 = 6.651 \times 10^{-25}; \quad \text{cm}^2 \quad (6)$$

$h\nu$  is the energy of the incident photon;  $M_0 c^2$  is the rest energy of the electron; and  $Z$  is the atomic number of the absorbing material. This formula applies only to the ejection of electrons from the K shell of the atom ( $\sim 80$  percent of the photoelectric effect) and assumes that the photon energy is small enough so that we can neglect relativistic effects but is still much larger than the K-shell binding energy. The photoelectric cross sections as a function of energy are given in Table 1.

Compton Effect. The total Compton cross section (elastic scattering and absorption) is given [Evans, 1955] by

$$\sigma_c = \frac{3}{4} \phi_0 \left\{ \frac{1 + \alpha}{\alpha^2} \left[ \frac{2(1 + \alpha)}{1 + 2\alpha} - \frac{1}{\alpha} \ln(1 + 2\alpha) \right] + \frac{1}{2\alpha} \ln(1 + 2\alpha) - \frac{1 + 3\alpha}{(1 + 2\alpha)^2} \right\}, \quad \text{cm}^2/\text{electron} \quad (7)$$

where  $\alpha = h\nu/M_0c^2$ . For  $\alpha \ll 1$ ,

$$\sigma_c = \phi_0 (1 - 2\alpha + 5.2\alpha^2 - 13.3\alpha^3 + \dots), \quad \text{cm}^2/\text{electron} \quad (8)$$

and for  $\alpha \gg 1$

$$\sigma_c = \frac{3}{8} \phi_0 \frac{1}{\alpha} \left[ \frac{1}{2} + \ln 2\alpha \right] \quad \text{cm}^2/\text{electron} \quad (9)$$

Values of the total Compton cross section are given in Table 2.

Electron-Positron Pair Production. The total pair-production cross section per nucleus is [Evans, 1955]

$$\begin{aligned} \sigma_{pr} &= \sigma_0 Z^2 \int_0^{h\nu - 2M_0c^2} \frac{P \, dT_+}{h\nu - 2M_0c^2} , \\ &= \sigma_0 Z^2 \bar{P} , \end{aligned} \quad \text{cm}^2/\text{nucleus} \quad (10)$$

where

$$\sigma_0 = \frac{1}{137} \left( \frac{e^2}{M_0c^2} \right)^2 = 5.80 \times 10^{-28} ; \quad \text{cm}^2/\text{nucleus} \quad (11)$$

$T_+$  is the kinetic energy of the positron produced;  $Z$  is the atomic number of the absorber;  $P$  is a dimensionless quantity that is a complicated function of  $h\nu$  and  $Z$ , varying between 0 (for  $h\nu \leq 2M_0c^2$ ) and about 20 (for  $h\nu = \infty$ ) for all values of  $Z$ ; and  $\bar{P}$  is the average value of  $P$ . Evans [1955] gives a plot of  $P$  as a function of  $T_+/(h\nu - 2M_0c^2)$ . Analytical integration of the equation for  $\sigma_{pr}$  is possible only for relativistic cases:

$$\sigma_{pr} = \sigma_0 z^2 \left( \frac{28}{9} \ln \frac{2h\nu}{M_0 c^2} - \frac{218}{27} \right) \quad M_0 c^2 < h\nu < 137 M_0 c^2 z^{-1/3}, \quad (12)$$

$$\sigma_{pr} = \sigma_0 z^2 \left[ \frac{28}{9} \ln (183 z^{-1/3}) - \frac{2}{27} \right] \quad h\nu > 137 M_0 c^2 z^{-1/3}. \quad (13)$$

Values of the pair-production cross section are given in Table 3.

To estimate the effect of gamma-ray absorption above the photosphere, we shall adopt a path length in the corona of three times the solar radius and overestimate the average electron density there by assuming it to be  $10^9 \text{ cm}^{-3}$  over the entire path. Using these values, we have

$$t_v = 2.1 \times 10^{20} (\sigma_v) \quad (14)$$

Likewise, if we adopt a density of  $3 \times 10^{13} \text{ electrons/cm}^3$  in the flare and a path length in the flare of  $10^9 \text{ cm}$ , then

$$t_v = 3 \times 10^{22} (\sigma_v) \quad (15)$$

The maximum value of  $\sigma_v$  in the defined gamma-ray energy region occurs at 10 kev. In the corona photoionization is negligible, since only a few nonabundant atoms retain even K-shell electrons. In most of the chromosphere and in the flare itself, the temperature is high enough so that hydrogen and helium are completely ionized. Therefore, at 10 kev

$$\sigma_v \approx \sigma_c, \quad (16)$$

and

$$t_v = 2.1 \times 10^{20} \sigma_c \approx 10^{-4} \quad (17)$$

for the corona, and

$$t_v = 3 \times 10^{22} \sigma_c \approx 10^{-2} \quad (18)$$

for flares. Thus gamma-ray absorption above the photosphere is negligible.

It is interesting to note that at high gamma-ray energies, e.g., greater than 50 Mev,  $\tau_v$  has its smallest value, and therefore, radiation of this energy produced within a depth of  $\sim 58 \text{ gm/cm}^2$  from the surface of sun will undergo little absorption.

#### IV. Properties of the Sun and Solar Flares Important to Gamma-Ray Production

Because of the absorption in the interior of the sun, we cannot detect gamma radiation originating at its center. We are therefore predominantly interested in surface reactions that can produce this radiation. We shall find that solar flares are the primary source of gamma radiation. In this section we shall summarize briefly the structure of the sun as related to chromospheric flares and establish a simple approximation to the nature of the interacting region that produces gamma rays.

Typical values of the temperature and density of the chromosphere and corona are given in Table 4 [Thomas and Athay, 1961; de Jager, 1959; Van de Hulst, 1953] .

A flare is defined as a sudden, short-lived brightening in  $H_\alpha$  of a local region on the sun's disk, occurring in the vicinity of a sunspot. Solar flares are classified according to their area and intensity as seen in the  $H_\alpha$  emission line. The approximate area and relative frequency of various types of flares are tabulated in Table 5 [de Jager, 1959; Beckers, 1962] . In the calculations that follow, we shall



take the area of a flare as seen against the disk of the sun to be  $10^{19}$  cm<sup>2</sup>. The observed area of a flare is a combination of two areas: the area of the side of the flare as it would be seen on the limb and the area of the top of the flare as seen at the center of the disk. Warwick [1955] has observed the change in measured areas of H<sub>α</sub> flares when seen at the center of the disk and at some distance from the center. The result of this work was a height-frequency distribution represented by  $e^{-\beta h}$ , where  $1/\beta = 20,300$  km. For purposes of calculation we shall take the mean thickness of a flare to be  $10^9$  cm.

The densities in a flare are slightly greater than the densities in the surrounding chromosphere, being of the order of  $2$  to  $3 \times 10^{13}$  H atoms/cm<sup>3</sup> [de Jager, 1959]. The electron density shall be taken as equal to the proton density. The relative abundances of other elements are given in Table 6 [Goldberg, Müller, and Aller, 1960; Aller, 1958], where we have assumed normal solar abundance in the flare.

Spectrographic measurements of the kinetic temperatures of flares, as derived from line broadening, give values of the order of  $10^5$  °K [Goldberg, Mohler, and Müller, 1958; Zirin, 1959]. We must point out that these results may be partially caused by mass motions in the line of sight and that the H<sub>α</sub> emission observed must come from a region surrounding the high temperature section of the flare, because in the high temperature section hydrogen would be completely ionized.

Magnetic fields of 100 to 200 gauss are observed in plage regions, and their strength may rise to a few thousand gauss in the flare itself [Leighton, 1959] .

High-energy particles accelerated and ejected by flares have been observed at the earth. The differential rigidity spectrum of flare protons observed at the earth is given [Freier and Webber, 1963] by

$$\frac{dN'}{dR} = N_0' e^{-R/R_0} , \quad \text{protons/cm}^2 \text{ sec volt (19)}$$

where  $R$  is the rigidity of the proton in volts, and  $N_0'$  and  $R_0$  are constants. The rigidity of a particle with momentum  $p$  and charge  $ze$  is given by

$$R = \frac{pc}{ze} , \quad (20)$$

where  $c$  is the velocity of light. When  $p$  is in units of  $ev/c$ ,  $R$  in volts is numerically equal to  $p/z$ . The kinetic energy,  $T$ , of a particle is related to its rigidity by

$$T = \left[ z^2 R^2 + (M_0 c^2)^2 \right]^{\frac{1}{2}} - M_0 c^2 \text{ ev} , \quad (21)$$

where  $M_0 c^2$  is the rest mass of the particle in electron volts, and  $R$  is measured in volts. Values of  $R_0$  and  $N_0'$  are given by Freier and Webber for various flares. For protons in the range of 1 Mev to over 2 Bev, the value of  $R_0$  for a given flare was constant but varied from flare to flare from 50 to 300 million volts.

For any given flare the value of  $R_0$  is the same for both protons and alpha particles. The intensity ratio of protons to alpha particles at the same rigidity,  $p/\alpha$ , varied from 1 to 50. In the majority of cases this value was one.

High-energy electrons accelerated by a flare have also been observed at the earth [Meyer and Vogt, 1962], but their spectrum and number cannot be determined by the observations.

Because we lack information about the particle rigidity spectrum produced at the sun by a flare, we shall assume an exponential rigidity spectrum for protons and alpha particles with values of  $R_0$  varying from 50 to 300 Mv. We shall also assume that electrons follow an exponential rigidity spectrum, but that the electron rigidity constant,  $R_0$ , may be of a different order of magnitude. We shall consider values of  $R_0$  for electrons from 110 Kv to 200 Mv.

It is certainly conceivable that at low energies, e.g., proton kinetic energy less than 30 Mev, an inverse power spectrum of the kinetic energy would produce a better fit to the data. Since we are concerned only with an order-of-magnitude calculation of the gamma-ray flux in this paper, however, we shall assume an exponential rigidity spectrum over all energies.

Estimates of the total number of protons at the sun accelerated by flares vary from  $10^{31}$  to  $10^{35}$  [Hofmann and Winckler, 1963; Peterson and Winckler, 1958, 1959; Friedman, 1963] for protons with energy greater than 10 Mev ( $R = 136$  Mv). The time for these particles to be ejected by the flare may vary from 10 to 1000 seconds. We shall take the total number of protons per second accelerated in flares to be  $N$ , where

$$N = N_0 \int_0^{\infty} e^{-R/R_0} DR, \quad \text{protons/sec (22)}$$

$$N = N_0 R_0 = 10^{32} \quad \text{protons/sec (23)}$$

We shall also assume that the total number of accelerated electrons produced by a flare is equal to the number of accelerated protons produced.

We shall take the ratio of the total number of alpha particles accelerated to the total number of protons accelerated to be the same as the ratio of normal solar abundances, 0.14. We shall neglect the effects of accelerated particles with  $Z > 2$ .

In order to calculate the gamma-ray production in a flare caused by high-energy particles, we shall consider  $10^{32}$  protons/sec,  $10^{32}$  electrons/sec, and  $1.4 \times 10^{31}$  alpha particles/sec interacting over an area of  $10^{19}$   $\text{cm}^2$  and through a depth of  $10^9$  cm. Isotropic production of gamma-ray photons will be assumed.

In all cases the gamma-ray flux at the earth in photons/ $\text{cm}^2$  sec will equal the total gamma-ray production at the sun per second divided by  $4\pi L^2 = 2.7 \times 10^{27}$   $\text{cm}^2$ , where  $L$  is the astronomical unit.

## V. Intensity and Spectrum of Gamma Radiation from the Sun

Let us now consider the gamma-ray production mechanisms proposed in Section II.

### (1) Synchrotron radiation

The electromagnetic radiation by an electron of total energy  $E$  in a magnetic field  $B$  has an intensity maximum at the frequency  $\nu_m$ , where

$$\nu_m = 1.26 \times 10^6 B_{\perp} \left( \frac{E}{M_0 c^2} \right)^2 \text{ sec}^{-1} ; \quad (24)$$

and  $B_{\perp}$  is the component of the magnetic field in gauss perpendicular to the particle velocity. For gamma-ray emission by this process,

$$\nu_m > 2.42 \times 10^{18} \text{ sec}^{-1} ,$$

and therefore, if we take  $B_{\perp} = 10^3$  gauss,

$$E_{\text{electron}} > 22 \text{ Bev} .$$

Even with an exponential rigidity spectrum of  $R_0 = 200$  Mv and  $N_0 = 5 \times 10^{29}$  electrons/sec Mv, the flux at the earth of  $\sim 10$  kev photons would be negligible. Results from bremsstrahlung radiation calculations indicate that  $R_0$  is much less than 70 Mv for electrons. Therefore, synchrotron radiation is not an important mechanism for gamma radiation.

### (2) Electron recombination with atoms (free-bound transitions)

The limit of the K series X-ray lines is a monotonically increasing function of  $Z$ , the atomic number of the atom. The highest  $Z$  of an atom of significant abundance in the corona is that of iron,  $Z = 26$ , whose K

series limit lies at 1.3 angstroms (7 kev). When we consider that atoms of higher Z have very small abundances in the corona and that few of these atoms are ionized to the K shell, it is evident that line radiation resulting from transitions within atoms (bound-bound transitions) cannot produce gamma radiation.

The energy of a photon emitted in a free-bound transition is equal to the sum of the kinetic energy of the electron plus the ionization energy of the atom. Therefore emission is possible below the wavelengths corresponding to the ionization potential. Even in the corona, however, with an electron kinetic temperature of  $10^6$  °K, iron is not ionized to the K shell. It exists in several ionization states, but the abundance of Fe XX and more highly ionized ferric ions is negligible. Recombination with these ions could produce gamma radiation only if the captured electron were in the extreme high-velocity tail of the electron distribution. The scarcity of these electrons and the small capture cross section for such high velocities makes such a process a negligible one.

When we consider that higher Z elements have a drastically lower abundance than iron, and that they, too, are not ionized to the K shell, we see that gamma rays cannot be produced by free-bound recombinations in the corona. Lower Z elements, although more abundant, require electrons with even higher energies to produce gamma radiation, allowing us to neglect them also. Since flare temperatures are lower than coronal temperatures, free-bound collisions can be neglected as producers of gamma radiation.

### (3) Decay of naturally radioactive nuclei

We can also eliminate naturally-occurring radioactive isotopes as sources of solar gamma radiation. The primary source of this type on the sun is potassium-40 ( $K^{40}$ ). It has a half-life of  $1.25 \times 10^9$  years, a terrestrial abundance of 0.01 per cent of all potassium, and decays by  $\beta^-$  emission accompanied by a 1.46 Mev gamma ray. Even if all solar potassium were in this isotopic form, the low abundance and long half-life would lead to infinitesimal fluxes at the earth. Isotopes with half-lives of less than  $10^5$  years would have disappeared from the outer regions of the sun, since the sun is at least  $10^9$  years old and no mixing occurs between the core, where new isotopes are produced, and the outer layers.

We shall consider the production of radioactive nuclei by reactions of the outer layers of the sun with energetic flare and cosmic-ray protons and alpha particles in the section on nucleon-nucleon reactions.

### (4) Inverse Compton effect

The inverse Compton effect consists of the transfer of energy from energetic particles to photons by means of collisions between the two. The average energy loss,  $\Delta E$ , of a particle of total energy  $E$  in such a collision with a photon of initial energy  $k$ , measured in the observer's rest frame, is [Feenberg and Primakoff, 1948; Donahue, 1948]

$$\Delta E = \gamma k' / [1 + k' / M_0 c^2] \quad , \quad (25)$$

where

$$k' = \gamma k (1 + \beta \cos \theta);$$

$$\beta = v/c;$$

$$v = \text{velocity of the particle};$$

$$\gamma = E/M_0 c^2;$$

$$M_0 c^2 = \text{rest energy of the particle};$$

$$(\pi - \theta) = \text{angle between the velocity vector of the particle and the velocity vector of the photon before collision.}$$

The equation for the energy loss by the electron assumes

$$k' < \frac{1}{2} M_0 c^2. \quad (26)$$

With  $\beta \approx 1$  and the average value of  $\beta \cos \theta$  equal to zero, the equation for  $\Delta E$  becomes

$$\Delta E \approx \gamma^2 k. \quad (27)$$

The average energy of the photons emitted by the sun is 1.4 ev; therefore, to transfer 10 kev to a thermal photon, electrons of approximately 43 Mev kinetic energy or protons of 80 Bev kinetic energy are necessary. Over the visible range (3000 to 6000 A) the energy emitted by the sun is  $7.4 \times 10^{10}$  ergs/cm<sup>2</sup> sec; during a flare this value might become 1.1 times as great [Parker, 1957]. Therefore the photon density at the sun is approximately  $10^{12}$  cm<sup>-3</sup>. With a solar constant of 1.94 cal/cm<sup>2</sup> min, and an average thermal photon energy of 1.4 ev, the photon density at the earth is about  $2 \times 10^7$  cm<sup>-3</sup>.



Making use of the method of Feenberg and Primakoff [1948] , we find the number of Compton collisions with thermal solar photons made by an electron traveling radially from the sun to the earth is  $8.7 \times 10^{-2}$  . A proton would make only  $2.6 \times 10^{-8}$  collisions.

The integral gamma-ray flux at the earth is then calculated by considering the total number of electrons for a given rigidity spectrum with energy greater than 50 Mev incident per second on the high photon-density region near the sun, where most of the collisions occur. The integral flux of photons at the earth with energy greater than 10 kev is given in Table 7.

As Table 7 shows, for  $R_0$  greater than 5 Mv the flux at the earth is detectable. Bremsstrahlung calculations, however, indicate that  $R_0$  for electrons is much less than 5 Mv. It must also be pointed out that since both inverse Compton and bremsstrahlung gamma rays have a continuous energy spectrum, the former will be masked by the latter unless the electron  $R_0$  is greater than 10 Mv. Since this does not seem to be the case, the inverse Compton effect is not an important gamma-ray source.

Stein and Ney [1963] have proposed that the white light produced by some flares is caused by synchrotron radiation of electrons with  $R_0 = 200$  Mv. If such electrons exist in a flare, a detectable gamma-ray flux at the earth resulting from the inverse Compton effect is possible [Gordon, 1960] .

(5) Electron bremsstrahlung

A mechanism that can produce a continuous spectrum of solar gamma radiation is electron bremsstrahlung. Bremsstrahlung can be considered the result both of free-free electron transitions caused by deceleration of high-energy electrons in the dense flare volume ( $N \sim 3 \times 10^{13} \text{ cm}^{-3}$ ) and of free-free transitions by electrons in a hot gas (thermal bremsstrahlung).

Bremsstrahlung by high-energy electrons appears to be predominant. The quantum mechanical expression for the energy radiated per unit path length in the frequency range  $\nu$  to  $\nu + d\nu$  by a particle of rest mass  $M_0$  in the field of a particle of charge  $Z$  is [Evans, 1955]

$$dW = N_Z \sigma_0 Z^2 (T + M_0 c^2) \bar{B}_{\nu \rightarrow \nu + d\nu} \frac{d(h\nu)}{T} \text{ ergs cm}^{-1}, \quad (31)$$

where

$$\sigma_0 = \frac{1}{137} (e^2/M_0 c^2)^2 = 0.580 \times 10^{-27} \text{ cm}^2;$$

$N_Z$  = number of particles of charge  $Z$  per  $\text{cm}^3$ ;

$T$  = kinetic energy of the particle;

$\bar{B}_{\nu \rightarrow \nu + d\nu}$  = the average value of a slowly varying function in the frequency interval  $\nu$  to  $\nu + d\nu$  [Bethe and Heitler, 1934].

Thus per unit path length the mean number of photons in the energy interval between  $h\nu$  and  $h\nu + d(h\nu)$  emitted per electron is  $dW/h\nu$ . The gamma-ray flux will be based on  $10^{32}$  electrons/sec passing through the flare volume ( $10^{19} \text{ cm}^2 \times 10^9 \text{ cm}$ ) with a spectrum given by

$$\frac{dN}{dR} = N_0 e^{-R/R_0}, \quad \text{electrons/sec volt (32)}$$

where

$$N_0 R_0 = 10^{32} \quad \text{electrons/sec}$$

and  $R$  is related to the kinetic energy  $T$  by

$$R = \frac{1}{Z} \left[ (T + M_0 c^2)^2 - (M_0 c^2)^2 \right]^{\frac{1}{2}}. \quad (33)$$

In the flare volume  $N_Z = 3 \times 10^{13} \text{ cm}^{-3}$ , and the average value of  $Z^2$  is 1.36

The number of gamma-ray photons per  $\text{cm}^2$  per sec in the frequency interval between  $\nu$  and  $\nu + d\nu$  at the earth is given by

$$dN_Y = \left[ \int_R \left( \frac{dW}{h\nu} \frac{dN}{dR} \right) dR (10^9) \right] / 2.7 \times 10^{27} \text{ cm}^{-2} \text{ sec}^{-1}. \quad (34)$$

We evaluated this integral numerically. The integral photon flux at the earth for a range of values of  $R_0$  is given in Table 8 and Table 9.

In a region where the density is  $3 \times 10^{13} \text{ protons cm}^{-3}$ , the electron spectrum is modified in seconds because of energy losses by synchrotron radiation and collisions in addition to bremsstrahlung. Stein and Ney [1963] give a comparison of the relative rate of energy loss. An accurate determination of the spectrum as a function of time is very difficult. The few gamma-ray spectra that are available [Friedman, 1963] indicate that the electron rigidity spectra have exponential decay constants,  $R_0$ , of less than 1 Mv.

Because of the lower densities in the chromosphere and corona regions outside of the flare volume, bremsstrahlung in these regions resulting from deceleration of high-energy electrons is negligible compared to bremsstrahlung in the flare volume.

Proton bremsstrahlung can be neglected compared to electron bremsstrahlung, since  $\sigma_0 \sim 1/M_0^2$ .

The intensity of the radiation from free-free electron transitions in a gas is given [Elwert, 1961; Stein and Ney, 1963] by

$$\begin{aligned}
 I &= \frac{16}{3} \left( \frac{\pi}{6} \right)^{\frac{1}{2}} \left( \frac{e^2}{M_0 c^2} \right)^2 (Ze)^2 \left( \frac{M_0 c^2}{kT} \right)^{\frac{1}{2}} \\
 &\times g_e e^{-h\nu/kT} N_e N_i \\
 &= 5.44 \times 10^{-39} Z^2 e^{-h\nu/kT} \left( \frac{1}{T^{\frac{1}{2}}} \right) N_e N_i \text{ erg/cm}^3 \text{ sec ster cps,}
 \end{aligned}
 \tag{35}$$

where

- $Z^2 = 1.36$ ;
- $M_0$  = electron mass;
- $k$  = Boltzmann's constant
- $= 8.616 \times 10^{-5} \text{ ev/deg}$ ;
- $g$  = Gaunt factor  $\approx 1$ ;
- $T$  = temperature of gas, measured in degrees Kelvin;
- $N_e$  = electron density;
- $N_i$  = proton density.

For emission over  $4\pi$  steradians from a volume of  $10^{28} \text{ cm}^3$ , where  $N_e = N_i = 3 \times 10^{13} \text{ cm}^{-3}$ , the integral gamma-ray flux at the earth is

given by

$$\begin{aligned}
 I_{\text{earth}} &= \frac{3.1 \times 10^{-10}}{T^{\frac{1}{2}}} \int_{10 \text{ kev}}^{\infty} e^{-hv/kT} dv \frac{\text{erg}}{\text{cm}^2 \text{ sec}} \\
 &= 6.5 \left( T^{\frac{1}{2}} \right) e^{-\frac{1.2 \times 10^8}{T}} \frac{\text{erg}}{\text{cm}^2 \text{ sec}} \quad (36)
 \end{aligned}$$

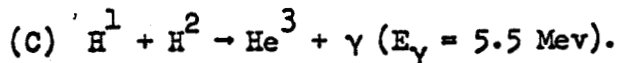
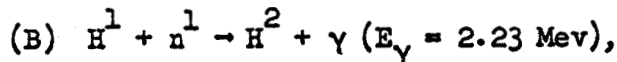
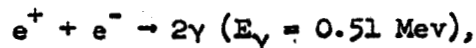
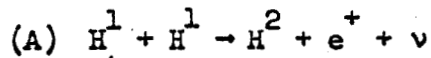
For temperatures of  $10^5$  or  $10^6$  °K, the flux at the earth is negligible.

The observed value of the flux for the 8/31/59 flare for  $hv > 20 \text{ kev}$  was  $4.5 \times 10^{-6} \text{ ergs/cm}^2 \text{ sec}$  [Chubb, Friedman, and Kreplin, 1960].

Temperatures of the order of  $10^7$  °K or higher could generate the observed flux. A gas at these temperatures, however, would not radiate in  $H_{\alpha}$ , and thus we cannot assume that the volume of the region emitting gamma rays is the same as that emitting  $H_{\alpha}$ . Although the duration of the 8/31/59 flare was of the order of minutes, other observed gamma-ray bursts occurred in seconds. Such rapid changes in the flux also rule out thermal origin from a large volume. At energies less than 10 kev, bremsstrahlung by thermal electrons may be the most important source of X-rays [Kawabata, 1960; de Jager, 1963; Friedman, 1963].

## (6) Nucleon-nucleon reactions

(a) Thermonuclear reactions. The kinetic temperature of flares and the corona is high enough so that thermonuclear reactions may occur. The energy liberated by mass conversion in these reactions can be in the form of gamma radiation or positrons which annihilate to form gamma radiation. The thermonuclear reactions most likely to produce gamma radiation, considering relative abundances and Coulomb barrier potentials, are



The reaction rate between two unlike particles is given by

$$r = n_1 n_2 \langle \sigma v \rangle, \quad \text{cm}^{-3} \text{ sec}^{-1} \quad (37)$$

where  $n_1$  and  $n_2$  are the number of reacting particles per  $\text{cm}^3$  and  $\langle \sigma v \rangle$  is the average of the product of the reaction cross section and the relative velocity of the reacting particles. For reactions between like particles,

$$r = \frac{n^2}{2} \langle \sigma v \rangle. \quad \text{cm}^{-3} \text{ sec}^{-1} \quad (38)$$

If the particles have a Maxwell-Boltzmann velocity distribution, then

[Gamow and Critchfield, 1949; Cameron, 1961; Salpeter, 1952]

$$r = \frac{7.25 n_1 n_2}{Z_1 Z_2 A_1 A_2} (10^{-22}) (A_1 + A_2) S \tau^2 e^{-\tau}, \quad \text{cm}^{-3} \text{ sec}^{-1} \quad (39)$$

where

$$\tau = 42.48 \left[ \frac{Z_1^2 Z_2^2 A_1 A_2}{A_1 + A_2} \right]^{1/3} T_6^{1/3};$$

$$S = \sigma E \exp \left\{ 988 Z_1 Z_2 \left[ \frac{A_1 A_2}{(A_1 + A_2) E} \right]^{1/2} \right\} \text{ ev barn};$$

$Z$  = atomic number;

$A$  = atomic mass number;

$T_6$  = temperature in units of  $10^6$  °K;

$E$  = energy corresponding to the relative

velocity  $v = \frac{1}{2} m v^2$ ;

$m$  = reduced mass =  $m_1 m_2 / (m_1 + m_2)$ ;

$\sigma$  = cross section for the reaction in barns  
( $10^{-24}$  cm<sup>2</sup>) at the energy  $E$ .

$S$  is a slowly varying function of the energy  $E$  and can be considered constant.

For reaction (A) the value of  $S$  is  $3.12 \times 10^{-19}$  ev barn [Salpeter, 1952]. The reaction rates and gamma-ray fluxes at the earth are given in Table 10. If we take the volume of the flare to be  $10^{28}$  cm<sup>3</sup>, the gamma-ray flux at 0.51 Mev is  $3 \times 10^{-30}$  photons/cm<sup>2</sup> sec at the earth.

In these calculations the positrons were assumed to annihilate instantaneously. We will discuss the positron-annihilation time in a later section.

For a corona volume of  $6.2 \times 10^{32}$  cm<sup>3</sup> (a hemispherical shell whose outer radius is 1.2 solar radii), a temperature of  $1.5 \times 10^6$  °K, and a density of  $10^9$  cm<sup>-3</sup>, the gamma-ray flux at the earth is  $7 \times 10^{-28}$  photons/cm<sup>2</sup> sec.

For a coronal condensation volume of  $1.2 \times 10^{30}$  cm<sup>3</sup> ( $1.2 \times 10^{22}$  cm<sup>2</sup>  $\times 10^8$  cm), a temperature of  $4 \times 10^6$  °K, and a density of  $5 \times 10^{10}$  cm<sup>-3</sup>, the flux at the earth is  $1.4 \times 10^{-25}$  photons/cm<sup>2</sup> sec.

In reaction (B), neutron capture by a proton to form deuterium, the reaction rate is given by

$$r = n_n n_p \langle \sigma v \rangle \quad \text{cm}^{-3} \text{ sec} \quad (40)$$

and

$$\sigma = \frac{7.30 \times 10^{-20}}{v} \quad \text{cm}^2 \quad (41)$$

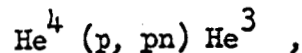
where  $n_n$  and  $n_p$  are the neutron and proton densities ( $\text{cm}^{-3}$ ). In the flare volume  $n_p = 3 \times 10^{13} \text{ cm}^{-3}$ ; consequently,

$$r = (2.2 \times 10^{-6}) n_n \quad \text{cm}^{-3} \text{ sec}^{-1} \quad (42)$$

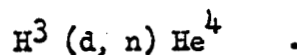
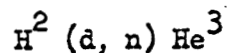
The gamma-ray flux at the earth is then

$$I = (8.1 \times 10^{-6}) n_n \quad \text{photons/cm}^2 \text{ sec} \quad (43)$$

Neutrons, with a half-life in the free state of 13 minutes, are not normally present at the solar surface. The neutrons originate from nuclear reactions of flare-accelerated protons and alpha particles with nuclei present in the flare region, primarily



and from thermonuclear reactions, primarily





Consideration of all (p, n), (p, pn), (p, 2n), ( $\alpha$ , n), ( $\alpha$ , np), and ( $\alpha$ , 2n) reactions with helium, carbon, and oxygen (see 6b) gives a neutron production rate of  $0.1 \text{ cm}^{-3} \text{ sec}^{-1}$  for  $R_0 = 70 \text{ Mv}$  and  $0.7 \text{ cm}^{-3} \text{ sec}^{-1}$  for  $R_0 = 200 \text{ Mv}$ . The mean neutron energy is a few Mev.

Post [1956] has discussed the thermonuclear reactions, and has calculated the reaction rate for a flare. For a deuteron density  $n_d \approx 10^{-5} n_p$ ,  $n_p = 3 \times 10^{13} \text{ cm}^{-3}$ , and a temperature of  $3.5 \times 10^5 \text{ }^\circ\text{K}$ , the neutron production rate from the d-d reaction is negligible.

Most of the neutrons produced in these reactions will escape from the flare region. Neutrons with an energy of 3 Mev have a velocity approximately equal to  $3 \times 10^9 \text{ cm/sec}$ . The total cross section for n-p reactions at this energy is  $\sim 3$  barns; thus, for  $n_p = 3 \times 10^{13} \text{ cm}^{-3}$ , the neutron mean free path is  $\sim 10^{10} \text{ cm}$ .

Because of the absence of neutrons in the corona and the low production of neutrons in this region during a flare, the gamma-ray flux from the entire corona caused by reaction (B) is negligible compared to production in the flare volume.

Although reaction (B) produces deuterium in the region of the flare, it is interesting to note that it would be in quantities far below that spectroscopically detectable. The only claim to have observed deuterium in a flare was based on an unsymmetrical  $H_\alpha$  line (the  $D_\alpha$  line being shifted 1.78 angstroms from the  $H_\alpha$  line) [Goldberg, Mohler, and Müller, 1958]. The deuterium abundance derived was from 1 to 4 per cent that of the hydrogen abundance, which compares with a normal abundance of less than  $4 \times 10^{-5}$  that of hydrogen [Righini, 1962]. The line asymmetry, never seen in any other flare, was probably caused by mass motions in the line of sight.

The reaction (C), involving deuterium as a reagent, is also a poor gamma-ray producer. The value of S for this reaction is  $7.8 \times 10^{-2}$  ev barn [Cameron, 1957]. Even assuming the deuterium abundance to be 18 per cent that of hydrogen in a flare, a flux at the earth of only  $1 \times 10^{-16}$  photons/cm<sup>2</sup> sec is obtained from this reaction. With an abundance of deuterium in the corona less than  $4 \times 10^{-5}$  that of hydrogen, the flux at the earth from this reaction would be less than  $9.5 \times 10^{-14}$  photons/cm<sup>2</sup> sec from the entire corona. For a coronal condensation at  $4 \times 10^6$  °K, the flux would be less than  $1.8 \times 10^{-10}$  photons/cm<sup>2</sup> sec.

(b) De-excitation of nuclei produced by nuclear reactions. Table 11 lists the proton-induced nuclear reactions of interest to this investigation, either because they produce gamma radiation directly, or because they produce it indirectly by positron formation, or because they produce neutrons.

The number of nuclear reactions per second, r, in the flare volume is given by

$$r = \int_{R_t}^{\infty} n_t \sigma_r l \frac{dN}{dR} dR, \quad \text{sec}^{-1} \quad (44)$$

where

$n_t$  = density of target nuclei (cm<sup>-3</sup>);

$\sigma_r$  = reaction cross section (cm<sup>2</sup>);

$l$  = interaction path length, which is equal to the flare thickness (cm);

$\frac{dN}{dR}$  = number of particles incident on the flare volume per second per volt;

$R_t$  = rigidity at threshold for the reaction.

Calculations of the reaction rate assume that the accelerated particles pass through the flare volume ( $10^{19} \text{ cm}^2 \times 10^9 \text{ cm}$ ) and interact over a distance of  $10^9 \text{ cm}$ . The target nuclei densities are given in Table 6. We take the proton flux to be  $10^{32}$  protons/sec over the flare area and assume an exponential rigidity spectrum (Section IV).

The reaction cross section can be written as the sum of the cross sections of individual inelastic reactions. In the energy range of interest, for proton reactions with a given target nucleus

$$\begin{aligned} \sigma_r = & \sigma(p, p') + \sigma(p, n) + \sigma(p, pn) + \sigma(p, 2p) \\ & + \sigma(p, 2n) + \sigma(p, \alpha) + \dots, \end{aligned} \quad (45)$$

where we have neglected higher-order terms as well as the reactions  $(p, \gamma)$  and  $(p, d)$ .

Using the optical model assumptions of Fernbach, Serber, and Taylor [1949] for a uniform density nucleus of radius  $\rho = \rho_0 A^{1/3}$ , we can approximate the reaction cross section [Wattenburg, 1957] by

$$\sigma_r = \pi \rho^2 \left[ 1 - \frac{1 - (1 + 2K\rho) e^{-2K\rho}}{2K^2 \rho^2} \right], \quad (46)$$

where  $K = 5 \times 10^{12} \text{ cm}^{-1}$ ,

and  $\rho_0 = (1.28 \pm 0.3) \times 10^{-13} \text{ cm}$

over the energy region where  $\sigma_r$  is approximately constant.

Direct gamma-ray emission results from these reactions because of decay of the excited states of the product nuclei. This decay usually occurs in less than  $10^{-10}$  second. This gamma-ray production rate in the flare is given by the product of the reaction rate,  $r$ , and the gamma-ray multiplicity per reaction,  $m$ . Table 12 gives the value of  $\sigma_r m$  as a function of energy for flare-accelerated protons interacting with helium, carbon, nitrogen, and oxygen. From the threshold energy of a few Mev to about 30 Mev, the predominant gamma-ray emission results from  $(p, p')$  reactions (inelastic scattering) on carbon [Burge, 1959], nitrogen [Oda et al., 1960], and oxygen [Kobayashi, 1960]. A multiplicity,  $m$ , of one was used for carbon, and a multiplicity of two was used for nitrogen and oxygen in this energy range [Scherrer, Theus, and Faust, 1953; Hofmann and Winckler, 1963]. The gamma-ray production rate decreases at higher energies although  $\sigma_r$  is constant, implying that in most reactions the end-product nucleus is produced in its ground state. For proton energies greater than 30 Mev, the value of  $\sigma_r m$  measured at 150 Mev [Foley, Solmon, and Clegg, 1962; Clegg, Foley, Solmon, and Segel, 1961] was used.

The gamma-ray emission caused by these reactions consists of line emission in the energy region from 0.5 to 10 Mev. For example, the predominant line emission from carbon is 4.43 Mev and from oxygen, 6.15 Mev. Over this energy region the gamma-ray flux at the earth for  $R_0 = 70$  Mv is  $0.16 \text{ photon/cm}^2 \text{ sec}$  and for  $R_0 = 200$  Mv is  $0.24 \text{ photon/cm}^2 \text{ sec}$ .

Assuming a ratio of  $\alpha$  particles to protons of 0.14 for the accelerated particles, and acceleration to the same rigidity spectrum, we can neglect  $\alpha$ -particle reactions.

Because of the drastically reduced target densities in the corona, nuclear-reaction rates there can be neglected in comparison with reaction rates in the flare itself.

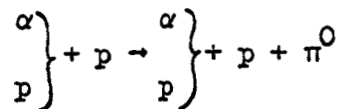
The gamma-ray fluxes predicted for this energy region are certainly detectable; little effort has been made, however, to investigate this portion of the spectrum.

(c)  $\pi^0$ -meson decay. At proton energies above 200 Mev the predominant mechanism of gamma-ray production is the decay of  $\pi^0$  mesons,

$$\pi^0 \rightarrow 2 \gamma ,$$

which are produced in proton-proton collisions. The decay time for the  $\pi^0$  meson is  $2 \times 10^{-16}$  second. For decay at rest each of the photons would have an energy of 70 Mev.

The cross section as a function of proton and  $\alpha$ -particle energy for the reactions



and also reactions for multiple meson production are given by Pollack and Fazio [1963]. We computed the gamma-ray flux at the earth as in section (b), using exponential rigidity spectra with  $R_0 = 70$  Mv and  $R_0 = 200$  Mv. For  $R_0 = 70$  Mv the flux ( $h\nu > 50$  Mev) at the earth is  $4.8 \times 10^{-6}$  photons/cm<sup>2</sup> sec, and for  $R_0 = 200$  Mv the flux is  $7.4 \times 10^{-2}$  photons/cm<sup>2</sup> sec. Note that the gamma-ray flux in this energy region

is highly dependent on the value of  $R_0$  and certainly indicates the presence of very high-energy particles in the flare. Neutral meson decay is the chief source of radiation for all energies above 50 Mev.

It is interesting to note that  $\pi^0$  mesons can also be produced by galactic cosmic-ray protons and  $\alpha$  particles interacting at the solar surface. The flux at the earth for photons with energy greater than 50 Mev caused by this effect is  $\sim 10^{-6}$  photons/cm<sup>2</sup> sec.

(7) Positron-electron annihilation.

Positrons generated as by-products of nuclear reactions on the sun can annihilate with electrons to form gamma radiation:

$$e^+ + e^- \rightarrow 2\gamma ,$$

where the gamma-ray energy is 0.51 Mev for annihilation at rest. The cross section for this reaction has a maximum when the positron total energy,  $E_+$ , approximately equals the positron rest mass energy,  $M_0 c^2 = 0.51$  Mev. At this energy the annihilation rate,  $r$ , is given by

$$r = n_+ n_- (\pi r_0^2) c , \quad \text{cm}^{-3} \text{ sec}^{-1} \quad (47)$$

where  $n_+$  and  $n_-$  = the positron and electron densities (cm<sup>-3</sup>);

$$\pi r_0^2 = 0.25 \times 10^{-24} ; \quad \text{cm}^2$$

$c$  = velocity of light.

Positrons are generated by the beta-decay of nuclei and the decay of  $\pi^+$  mesons.

(a) Beta-decay of nuclei. The nucleon-nucleon reactions discussed above, in addition to producing nuclei in excited states, also produce nuclei which are radioactive and decay by positron emission. The gamma-ray flux resulting from the subsequent positron annihilation depends not only on the rate of production of the radioactive nuclei but also on the mean lifetime for decay. The only nuclei which can contribute significantly to the gamma-ray flux are those that decay with a mean lifetime less than or approximately equal to the total time,  $t_0$ , that the accelerated protons interact with the flare. The rate of decay at time  $t$  after the protons initially interact is given, for  $t \leq t_0$ , by

$$\dot{\Phi} = r (1 - e^{-\lambda t}) , \quad \text{sec}^{-1} \quad (48)$$

where

$r$  = constant rate of production of the radioactive nuclei;

$\lambda$  = decay constant =  $1/\tau$  ;

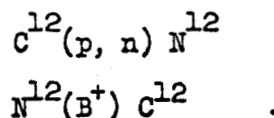
$\tau$  = mean lifetime.

At  $t = t_0$  the production ceases and the rate of decay becomes, for  $t > t_0$ ,

$$\dot{\Phi} = r e^{-\lambda(t-t_0)} (1 - e^{-\lambda t_0}) . \quad \text{sec}^{-1} \quad (49)$$

For an interaction time  $t_0 = 100$  seconds in a flare, the principal sources of positrons, based on reaction rates and decay times, for proton and  $\alpha$ -particle-induced reactions are given in Table 13. The average cross sections assumed in Table 13 were calculated by Chupp [1963] and are estimated from

compound nucleus formation cross sections by assuming all decay channels equally probable. The most important source of positrons is



For this reaction the gamma-ray flux at the earth is  $3.4 \times 10^{-3}$  photons/cm<sup>2</sup> sec for  $R_0 = 70$  Mv and  $2.1 \times 10^{-2}$  photons/cm<sup>2</sup> sec for  $R_0 = 200$  Mv.

For these fluxes the positron was assumed to annihilate instantaneously. This is not the actual situation. The total time from production to annihilation is the sum of the time needed for the positron to lose energy by synchrotron radiation and ionization to a final total energy of  $\sim 0.5$  Mev, plus the time for annihilation at this energy.

The rate of energy loss is given [Ginzburg, 1958] by

(1) magnetic bremsstrahlung,

$$dE/dt = -4 \times 10^{-15} E^2 B_{\perp}^2 = -bE^2 \text{ ev/sec ;} \quad (50)$$

(2) collision in ionized hydrogen,

$$dE/dt = -7.62 \times 10^{-9} n \left( \ln \frac{E}{mc^2} - \ln n + 7.46 \right) \text{ ev/sec} \quad (51)$$

$$\approx -a ,$$

$$\text{ev/sec}$$

where  $E$  is the total energy of the positron;  $B_{\perp}$  is the component of the magnetic field in gauss perpendicular to the motion;  $n$  is the proton density;  $mc^2$  is the rest energy of the positron (0.511 Mev), and  $a$  and  $b$  are constants.



The total rate of energy loss is

$$dE/dt = -a - bE^2, \quad \text{ev/sec (52)}$$

where

$$a = 10^7;$$

$$b = 10^{-9};$$

$$B_{\perp}^2 = 2.5 \times 10^5 \text{ gauss}^2;$$

$$n = 3 \times 10^{13} \text{ cm}^{-3}.$$

Solving the above equation for  $t$ , we have

$$t = \frac{\tan^{-1} \left[ (b/a)^{\frac{1}{2}} E_0 \right] - \tan^{-1} \left[ (b/a)^{\frac{1}{2}} E \right]}{(ab)^{\frac{1}{2}}},$$

where

$$E = E_0 \text{ at } t = 0.$$

For  $E_0 = 10 \text{ Mev}$  and  $E = 0.5 \text{ Mev}$ ,  $t \approx 1 \text{ sec}$ .

The annihilation time is

$$t_a = 1/n_- m_0^2 c \approx 4 \text{ sec}$$

for

$$n_- = 3 \times 10^{13} \text{ cm}^{-3}.$$

Therefore, the total time from production to annihilation is approximately 5 seconds.

(b) Meson decay. An additional source of positrons is the decay of  $\pi^+$  mesons produced in proton-proton and proton- $\alpha$ -particle reactions:

$$\left. \begin{matrix} p \\ \alpha \end{matrix} \right\} + p \rightarrow \pi^+ + n + \left\{ \begin{matrix} p \\ \alpha \end{matrix} \right.$$

$$\pi^+ \rightarrow u^+ + \nu \quad (\tau = 2.6 \times 10^{-8} \text{ sec})$$

$$u^+ \rightarrow e^+ + \nu + \bar{\nu} \quad (\tau = 2.2 \times 10^{-6} \text{ sec})$$

The threshold for the p-p reaction is 290 Mev and for the p- $\alpha$  reaction, 172 Mev. Multiple meson production is possible at higher energies.

The production of  $\pi$  mesons, including cross sections and multiplicities, was previously considered by Pollack and Fazio [1963]. Note that just above threshold energy to approximately 1 Bev, the production of  $\pi^+$  mesons dominates the production of  $\pi^0$  mesons.

For a typical positron energy of 100 Mev, the time from production to annihilation is about 8 seconds.

The gamma-ray flux at the earth produced by positrons from beta-decay and meson decay is given in Table 14 for two values of  $R_0$  :  $R_0 = 70$  Mv and  $R_0 = 200$  Mv.

## VI. Modification of Calculated Fluxes

Because of the wide variations in the parameters involved in the calculation of gamma-ray fluxes from solar flares, all calculations in this paper are based on simple representative values. Fortunately, most of the results are directly proportional to the parameters which change from flare to flare, and can easily be converted to any observed set of

parameters for a given flare. The most important parameters are the area of the flare; the number of protons, electrons, and alpha particles interacting in the flare per second; and the exponential decay constant,  $R_0$ , of the particle spectrum. Only the last of the three parameters requires any amount of recalculation other than multiplication, and in this case the photon fluxes have been calculated for a range of values of  $R_0$ .

Such other quantities as the density of the atomic species and the path length of particles through the flare may also change in value from flare to flare. Since these quantities are difficult to determine for any one flare, it is probably best to use the values available for an average flare.

## VII. Summary

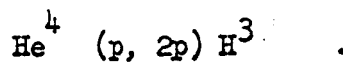
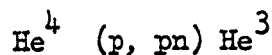
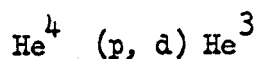
The gamma-ray spectrum of the sun is simple in its qualitative aspects and can yield valuable information on the nature of solar flares. Almost all gamma-ray activity will be associated with a flare region. The spectrum from 10 kev to a few Mev consists of continuous radiation, caused primarily by electron bremsstrahlung, which monotonically decreases in intensity with increasing energy. Line emission occurs at 0.51 kev because of positron annihilation; at 2.23 Mev, because of deuteron formation; and throughout the spectrum from 0.5 to 10 Mev because of nuclear de-excitation. The most important line emissions caused by the de-excitation process are at 4.43 Mev, from  $C^{14}$ , and at 6.14 Mev, from  $O^{16}$ .

All the above sources of line emission indicate the occurrence of nuclear reactions during a flare. The intensity of the 2.23 Mev line is a measure of the neutron density in a flare. The gamma-ray flux above 50 Mev is primarily caused by  $\pi^0$ -meson decay, which produces a continuous spectrum peaking at about 100 Mev. The flux in this energy region is very sensitive to the value of  $R_0$  and can yield much information about the accelerated particle spectrum in the flare. In discussing the detectability of line emission, we must remember that the strength of the continuum background radiation in relation to the line intensity determines just how easily the line may be detected. The 0.51 Mev line will be in the bremsstrahlung continuum and will therefore be difficult to detect. The 2.23 Mev line and the line emission caused by nuclear de-excitation are relatively free of this background. The deuteron line may be difficult to detect, depending on the neutron density; the de-excitation gamma rays should, however, be easily detectable in a large flare. At present little effort has been made to search for these lines.

Almost all solar gamma radiation is caused by flares. The only radiation that should emanate from a completely quiet sun is that resulting from the interaction of galactic cosmic rays with the solar photosphere. The occurrence, even during quiet periods, of many class 1- flares and sub-flares, however, may result in small, irregular fluxes of gamma radiation.

The present status of the detection of X-rays and gamma rays from the sun has been summarized by Friedman [1963] . The highest-energy photons detected were in the 300 to 500 kev region [Peterson and Winckler, 1959] , and all gamma rays detected thus far give spectra indicative of electron bremsstrahlung. All of the radiation has occurred in bursts associated with flares. Present upper limits on other portions of the spectrum are given by the results of experiments aboard the first Orbiting Solar Observatory [Lindsay, 1963] . The sensitivity of present detectors in the 0.1 to 3.0 Mev energy region is about 1 photon/cm<sup>2</sup> sec and above the 50 Mev region, ~ 10<sup>-3</sup> photon/cm<sup>2</sup> sec. No experiments have so far been performed in the 3.0 to 50 Mev region.

The only indication of nuclear reactions in a solar flare has been the detection of H<sup>3</sup> and He<sup>3</sup> in the exposed section of a satellite (Discoverer 17) during a class 3+ flare on November 12, 1960 [Fireman, DeFelice, and Tilles, 1961; Schaeffer and Zähringer, 1962; Hamm, Lingenfelter, MacDonald, and Libbey, 1962] . Both H<sup>3</sup> and He<sup>3</sup> could be produced by the reactions



To better understand the processes occurring during a solar flare we must investigate the gamma-ray portion of the electromagnetic spectrum emitted by a flare. Because of local background radiation, the construction of sensitive, directional detectors is not easy but is worth pursuing. Space vehicles such as the Orbiting Solar Observatories are available to carry gamma-ray detectors, and we urge that experiments be planned for the coming maximum of the solar cycle to thoroughly investigate this portion of the spectrum.

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TABLE 1. PHOTOELECTRIC CROSS SECTION

Photon Energy (kev)	$\sigma_{ph}/Z^5$ (cm <sup>2</sup> /atom)
10	$1.34 \times 10^{-26}$
50	$4.78 \times 10^{-29}$
100	$4.24 \times 10^{-30}$
500	$1.51 \times 10^{-32}$
1000	$1.34 \times 10^{-33}$

TABLE 2. COMPTON TOTAL CROSS SECTION

Photon Energy (Mev)	$\sigma_c/Z$ ( $10^{-25}$ cm <sup>2</sup> /atom)
0.010	6.40
0.102	4.90
0.511	2.87
1.02	2.09
5.11	0.817
10.22	0.502
51.10	0.143

TABLE 3. PAIR PRODUCTION CROSS SECTION

Photon Energy (Mev)	$\sigma_{pr}/Z^2$ ( $10^{-27}$ cm <sup>2</sup> /atom)
1.02	0
1.53	0.050
2.04	0.189
3.07	0.524
5.11	1.15
10.2	2.12
25.4	3.56

TABLE 4. PROPERTIES OF SOLAR CHROMOSPHERE AND CORONA

(A) Chromosphere

Height (km)	Temperature (°K)	Atom Density (cm <sup>-3</sup> )
500	6250	$6.2 \times 10^{13}$
750	--	$9.9 \times 10^{12}$
1000	7500	$1.15 \times 10^{12}$

(B) Corona

Height (km)	Temperature (°K)	Proton Density (cm <sup>-3</sup> )
$7.5 \times 10^3$	--	$3.0 \times 10^9$
$1.0 \times 10^4$	--	$7.9 \times 10^8$
$1.5 \times 10^4$	--	$4.2 \times 10^8$
$2.1 \times 10^4$	$1.0 \times 10^6$	$2.9 \times 10^8$
$1.4 \times 10^5$	$1.5 \times 10^6$	$4.0 \times 10^7$
$7.0 \times 10^5$	$1.5 \times 10^6$	$1.6 \times 10^6$
$1.4 \times 10^6$	$1.5 \times 10^6$	$3.0 \times 10^5$

TABLE 5. PROPERTIES OF CHROMOSPHERIC FLARES

Class	Optical Duration (min.)	Relative Frequency	Mean Area on Disk (cm <sup>2</sup> )
1-			$2.2 \times 10^{18}$
1	4-43	0.72	$4.8 \times 10^{18}$
2	10-40	0.25	$1.0 \times 10^{19}$
3	20-155	0.03	$2.9 \times 10^{19}$
3+	50-430		$3.6 \times 10^{19}$



TABLE 6. RELATIVE SOLAR ABUNDANCES OF ELEMENTS

Element	Relative Abundance	Flare Density ( $\text{cm}^{-3}$ )
H	1	$3.0 \times 10^{13}$
He	0.14	$4.2 \times 10^{12}$
C	$5.2 \times 10^{-4}$	$1.6 \times 10^{10}$
N	$9.5 \times 10^{-5}$	$2.8 \times 10^9$
O	$9.1 \times 10^{-4}$	$2.7 \times 10^{10}$

TABLE 7. INTEGRAL GAMMA-RAY FLUXES AT THE EARTH DUE TO  
INVERSE COMPTON EFFECT

$R_0$ (volts)	No. of Electrons ( $E > 50$ Mev)	Photons/cm <sup>2</sup> sec ( $E_\gamma > 10$ kev)
$2.0 \times 10^8$	$8.1 \times 10^{31}$	$2.6 \times 10^3$
$7.0 \times 10^7$	$5.1 \times 10^{31}$	$1.6 \times 10^3$
$1.0 \times 10^7$	$6.1 \times 10^{29}$	$2.0 \times 10^1$
$5.0 \times 10^6$	$3.8 \times 10^{27}$	$1.2 \times 10^{-1}$
$8.0 \times 10^5$	$7.1 \times 10^4$	$2.3 \times 10^{-24}$

TABLE 8. INTEGRAL GAMMA-RAY FLUX ( $N_\gamma$ ) AT THE EARTH DUE TO ELECTRON BREMSSTRAHLUNG

Photon Energy ( $E_\gamma$ )	$N_\gamma$ ( $\text{cm}^{-2} \text{sec}^{-1}$ ) $> E_\gamma$			
	$R_0 = 2 \times 10^8$ volts	$R_0 = 7 \times 10^7$ volts	$R_0 = 10^7$ volts	$R_0 = 5 \times 10^6$ volts
10 kev	172	150	116	105
20	162	141	105	93
30	150	129	91	77
40	132	123	85	70
50	140	118	80	65
100	126	105	65	51
200	113	91	51	37
300	105	83	43	30
400	99	77	37	25
500	94	73	34	22
1 Mev	81	59	23	13
5	51	31	5.9	1.8
10	39	22	2.2	0.37
50	16	4.8	$1.3 \times 10^{-2}$	$5.0 \times 10^{-5}$
100	8.0	1.5	$6.8 \times 10^{-5}$	--
500	0.40	$2.0 \times 10^{-3}$	--	--
1000	$2.2 \times 10^{-2}$	$1.6 \times 10^{-6}$	--	--

TABLE 9. INTEGRAL GAMMA-RAY FLUX ( $N_\gamma$ ) AT THE EARTH DUE TO ELECTRON BREMSSTRAHLUNG

Photon Energy ( $E_\gamma$ )	$N_\gamma$ ( $\text{cm}^{-2} \text{sec}^{-1}$ ) $> E_\gamma$			
	$R_0 = 8 \times 10^5$ volts	$R_0 = 5 \times 10^5$ volts	$R_0 = 3.5 \times 10^5$ volts	$R_0 = 1.1 \times 10^5$ volts
10 kev	71	65	60	33
20	56	47	42	21
30	36	28	22	5.6
40	30	22	16	3.3
50	25	17	12	2.1
100	15	8.7	5.3	0.37
200	7.9	3.9	1.9	0.045
300	5.0	2.2	0.94	$8.7 \times 10^{-3}$
400	3.4	1.3	0.53	$2.2 \times 10^{-3}$
500	2.4	0.85	0.30	$4.6 \times 10^{-4}$
600	1.7	0.56	0.18	$1.7 \times 10^{-4}$
800	0.95	0.25	0.066	$1.8 \times 10^{-5}$
1 Mev	0.57	0.12	0.025	$9.1 \times 10^{-7}$
3	$1.3 \times 10^{-2}$	$6.0 \times 10^{-4}$	$2.4 \times 10^{-5}$	--
5	$1.0 \times 10^{-3}$	$1.0 \times 10^{-5}$	$9.1 \times 10^{-8}$	--

TABLE 10.  $H' + H' \rightarrow H^2 + e^+ + \nu$  REACTION RATE

Solar Region	Temperature ( $^{\circ}K$ )	Proton Density ( $cm^{-3}$ )	Reaction Rate ( $cm^{-3} sec^{-1}$ )
Flare	$1 \times 10^5$	$3 \times 10^{13}$	$2.76 \times 10^{-41}$
	$3.54 \times 10^5$	$3 \times 10^{13}$	$7.37 \times 10^{-31}$
Corona	$8 \times 10^5$	$2 \times 10^8$	$1.97 \times 10^{-36}$
	$8 \times 10^5$	$10^9$	$4.93 \times 10^{-35}$
	$1.5 \times 10^6$	$2 \times 10^8$	$1.27 \times 10^{-33}$
	$1.5 \times 10^6$	$10^9$	$3.18 \times 10^{-32}$
Coronal Condensation	$2.5 \times 10^6$	$5 \times 10^{10}$	$5.14 \times 10^{-27}$
	$4 \times 10^6$	$5 \times 10^{10}$	$1.38 \times 10^{-25}$

TABLE 11. ACCELERATED PROTON REACTIONS FOR THE  
PRODUCTION OF GAMMA RADIATION AND NEUTRONS

Reaction	Proton Threshold Kinetic Energy (Mev)
$\text{He}^4 (p, pn) \text{He}^3$	25.6
$\text{He}^4 (p, 2pn) \text{H}^2$	32.5
$\text{He}^4 (p, 2p 2n) \text{H}^1$	35.2
$\text{C}^{12} (p, n) \text{N}^{12}$	19.9
$\text{C}^{12} (p, pn) \text{C}^{11}$	20.3
$\text{C}^{12} (p, 2p) \text{B}^{11}$	16.7
$\text{N}^{14} (p, n) \text{O}^{14}$	6.4
$\text{N}^{14} (p, pn) \text{N}^{13}$	11.3
$\text{N}^{14} (p, 2p) \text{C}^{13}$	12.3
$\text{N}^{14} (p, \alpha) \text{C}^{11}$	1.5
$\text{O}^{16} (p, np) \text{O}^{15}$	16.7
$\text{O}^{16} (p, 2p) \text{N}^{15}$	12.3
$\text{O}^{16} (p, \alpha) \text{N}^{13}$	5.0

TABLE 12. CROSS SECTIONS FOR GAMMA-RAY PRODUCTION BY  
NUCLEAR DE-EXCITATION

Target Nucleus	Flare Density ( $\text{cm}^{-3}$ )	Energy Region (Mev)	$\sigma_{\gamma m}$ (mb)
$\text{He}^4$	$4.2 \times 10^{12}$	> 4	0
$\text{C}^{12}$	$1.6 \times 10^{10}$	4-30 > 30	242 23
$\text{N}^{14}$	$2.8 \times 10^9$	4-30 > 30	558 27
$\text{O}^{16}$	$2.7 \times 10^{10}$	6-30 > 30	560 50

TABLE 13. PRINCIPAL SOURCES OF NUCLEI WHICH DECAY BY  $\beta^+$  EMISSION

No.	Reaction	$\tau$ (sec)	Threshold Energy (Mev)	Average Cross Section (mb)	Nuclear Reaction Rate ( $10^{-4} \text{ cm}^{-3} \text{ sec}^{-1}$ )	
					$R_0 = 70 \text{ Mv}$	$R_0 = 200 \text{ Mv}$
1.	$\text{C}^{12} (\text{p}, \text{n}) \text{N}^{12}$ $\text{N}^{12} (\beta^+) \text{C}^{12}$	0.0125	19.9	46.0	5.6	30
2.	$\text{N}^{14} (\text{p}, \text{n}) \text{O}^{14}$ $\text{O}^{14} (\beta^+) \text{N}^{14}$	72	6.4	53.3	3.4	8.8
3.	$\text{O}^{16} (\text{p}, \text{np}) \text{O}^{15}$ $\text{O}^{15} (\beta^+) \text{N}^{15}$	124	16.7	52.9	16.2	60
4.	$\text{C}^{12} (\alpha, \text{n}) \text{O}^{15}$ $\text{O}^{15} (\beta^+) \text{N}^{15}$	124	11.4	22.7	0.26	1.86
5.	$\text{C}^{12} (\alpha, 2\text{n}) \text{O}^{14}$ $\text{O}^{14} (\beta^+) \text{N}^{14}$	72	29.0	30.3	0.13	1.80
6.	$\text{N}^{14} (\alpha, \text{n}) \text{F}^{17}$ $\text{F}^{17} (\beta^+) \text{O}^{17}$	66	6.1	0.6	$1.7 \times 10^{-3}$	$9.4 \times 10^{-3}$
7.	$\text{O}^{16} (\alpha, \text{n}) \text{Ne}^{19}$ $\text{Ne}^{19} (\beta^+) \text{F}^{19}$	17.7	15.2	26.3	1.1	3.2
8.	$\text{O}^{16} (\alpha, 2\text{n}) \text{Ne}^{18}$ $\text{Ne}^{18} (\beta^+) \text{F}^{18}$	1.6	29.6	33.7	0.24	3.2



TABLE 14. GAMMA-RAY FLUX AT THE EARTH DUE TO  
POSITRON ANNIHILATION

Source Reaction	Flux (Photons/cm <sup>2</sup> sec)	
	R <sub>0</sub> = 70 Mv	R <sub>0</sub> = 200 Mv
$C^{12} (p, n) N^{12}$ $N^{12} (\beta^+) C^{12}$	$3.4 \times 10^{-3}$	$2.1 \times 10^{-2}$
$\pi^+ \rightarrow \mu^+ + \nu$ $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$	$5.7 \times 10^{-5}$	$4.2 \times 10^{-1}$